COST ESTIMATING RISK AND COST ESTIMATING UNCERTAINTY GUIDELINES

Timothy P. Anderson and Jeffrey S. Cherwonik

The Memorandum of Agreement signed by the Assistant Secretaries of the Navy for Research, Development, and Acquisition (ASN[RD&A]) and for Financial Management and Comptroller (FM&C) in June 1996 committed the Naval Center for Cost Analysis (NCCA) to improve cost analyses by helping program managers prepare better cost estimates. Recent computing advances make development of meaningful risk and uncertainty analyses easier, and these analyses can help managers do their job better.

The Memorandum of Agreement signed by the Assistant Secretaries of the Navy for Research, Development, and Acquisition (ASN[RD&A]) and for Financial Management and Comptroller (FM&C) on June 14, 1996, committed the Naval Center for Cost Analysis (NCCA) to "contribute to a more efficient Department of the Navy (DON) cost analysis process by assisting program managers prepare high-quality cost estimates for the acquisition chain of command…." One very important cost analysis issue that has received limited attention in the past by both NCCA and the program managers is "cost estimating risk and uncertainty."

Historically, program office estimates (POEs) as well as independent cost estimates (ICEs) have emphasized point rather than range estimates. With recent advances in computing capability, it has become quite easy to develop meaningful risk and uncertainty analyses that can provide significant insight to program managers and milestone decision authorities (MDAs).

This article will explain why we should analyze cost estimating risk and uncertainty, delineate responsibilities, describe the procedures required, and help clarify the process using a sample problem.

BACKGROUND

WHY ANALYZE COST ESTIMATING RISK AND UNCERTAINTY?

The typical DoD life cycle cost estimate (LCCE) is developed by calculating the estimated cost of each of several work

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **Cost Estimating Risk and Cost Estimating Uncertainty Guidelines**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Operations Research Department,Monterey,CA,93943**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Acquisition Review Quarterly, Summer 1997

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

breakdown structure elements and then adding them to derive a total LCCE. If the cost estimate for each work breakdown structure element represents the "best guess" of the cost for that particular element, then the sum of the cost estimates for each element represents, approximately, the "best guess" of the cost estimate for the whole system. Right? Wrong!

The above procedure has been in use for years. But the LCCE that results from this procedure is virtually guaranteed to be wrong! Assuming the estimate for each work breakdown structure element represents the mean or average cost for that element, then the only thing one can positively say about the resulting total cost point estimate is that it is the most likely cost out of a practically infinite number of possible costs.

Moreover, if all cost data come from a symmetric population (which they rarely do), then one can say that the total cost point estimate represents the 50th percentile cost. The interpretation of this is that the LCCE actually says "there is a 50 percent chance that the life cycle cost will be less than the point estimate; likewise, there is a corresponding 50 percent chance that the life cycle cost will be greater than the point estimate." Yet, unfortunately, this estimate says nothing about the range of possible costs. Is the estimate, say, $500 million plus or minus $10 million? Or is the estimate $500 million plus or minus $400 million? Obviously, this information could be of vital interest to a program manager or a milestone decision authority.

Here's What the CAIG Has to Say About It

The Cost Analysis Improvement Group (CAIG) has delineated its own ideas concerning cost estimating uncertainty in DoD 5000.4–M, "Cost Analysis Guidance and Procedures." In this document the CAIG says:

> Areas of cost estimating uncertainty will be identified and quantified. Uncertainty will be quantified by the use of probability distributions or ranges of cost. The presentation of this analysis should address cost uncertainty attributable to estimating errors; e.g., uncertainty inherent with estimating costs based on as-

LCDR Timothy Anderson is a military instructor in the Operations Research Department at the Naval Postgraduate School, Monterey, CA. He earned his M.S. degree in operations research from the Naval Postgraduate School in 1994. He is a member of the Society of Cost Estimating and Analysis, the Institute for Operations Research and Management Science, and the Military Operations Research Society. In his previous assignment he was an operations research analyst at the Naval Center for Cost Analysis, where he developed life cycle cost estimates for major weapons system acquisitions.

Jeffrey Cherwonik is an operations research analyst at the Naval Center for Cost Analysis (NCCA) supporting the Assistant Secretary of the Navy (Financial Management and Comptroller) in the area of cost analysis. He has been with NCCA since 1990, developing life cycle cost estimates of major Navy acquisition weapon systems. He earned his M.B.A. degree from the State University of New York at Buffalo, where he concentrated in both operations research and financial management, and has an engineering degree from Carnegie-Mellon University. He is also a member of the Institute for Operations Research and Management Science.

> sumed values of independent variables outside data base ranges, and uncertainty attributed to other factors, such as performance and weight characteristics, new technology, manufacturing initiatives, inventory objectives, schedules, and financial condition of the contractor. The probability distributions, and assumptions used in preparing all range estimates, shall be documented…

Clearly then, there is well-documented interest in cost estimating uncertainty and risk at the highest levels of DoD.

What Is the Difference Between Risk and Uncertainty?

Ask any two people for the definitions of risk and uncertainty and you will likely get two different answers. In addition, definitions vary among organizations. However, in the context of cost estimation, it is very important to have a precise definition of these two terms. NCCA has defined the two terms in the following way.

Cost estimating uncertainty. Uncertainty reflects one's confidence in the point estimate. Cost estimating uncertainty arises from the inaccuracies inherent in the cost estimating methodologies. For example, one might estimate a work breakdown structure element using a cost estimating relationship (CER) that, based on its underlying data, is accurate to within plus or minus some percentage. Consider the following CER.

> Cost (FY96$K) = 3.06 x (Weight in lbs)$^{0.551}$
> Standard Error - 0.20 (+22.1%, – 18.1%)

In this example, if the weight of the object being estimated is 100 pounds, then the estimated cost would range from $31.7K to $47.3K. The uncertainty in the estimate is captured by specifying the range (in this case $31.7K to $47.3K) in which the true cost of the object is likely to occur based on inaccuracies in the cost estimating methodology.

Cost estimating risk. Risk reflects one's confidence in the input parameters used to develop a cost estimate. Cost estimating risk arises from the inaccuracies inherent in the programmatic assumptions or technical data used as inputs to CERs. Consider the CER shown previously.

> Cost (FY96$K) = 3.06 x (Weight in lbs)$^{0.551}$
> Standard Error - 0.20 (+22.1%, – 18.1%)

If the weight of the object being estimated is 100 pounds plus or minus 5 pounds, then there exists another source of cost estimating error. First, the analyst has to account for the risk associated with

Table 1. Estimate Containing Elements of Risk and Uncertainty

	CER – 18.1%	BASELINE CER	CER + 22.1%
95 lbs	$30.8K	$37.6K	$45.9K
100 lbs	$31.7K	$38.7K	$47.3K
105 lbs	$32.6K	$39.8K	$48.6K

the variance in the input parameter (5 pounds); then the analyst must deal with the uncertainty in the CER (+22.1%, –18.1%). Table 1 shows the steps needed to get at the final answer.

In this example, the estimated cost would range from $30.8K to $48.6K after considering both uncertainty and risk. Notice the wider range associated with both uncertainty and risk compared to the range associated with uncertainty alone.

RESPONSIBILITIES

Since cost estimates are now typically done by integrated product teams (IPTs), the responsibility for gathering data and documenting areas of risk and uncertainty will in most cases rest with the Cost IPT (CIPT). Exactly which analyst performs which function will be decided within each CIPT.

Ordinarily, the cost analyst will be responsible for selecting the methodology for estimating the cost of each work breakdown structure element. An important part of this responsibility is to ensure the statistics (uncertainty) associated with the cost estimating methodologies are known or are quantifiable. Often, the cost analyst will estimate cost with a single point analogy or an engineering buildup for which no apparent statistics exist. In these cases, the analyst should make every effort to go back to the source of the estimate and obtain a subjective probability or range assessment for these costs. As a minimum, the analyst should consider the variability reflected in previous cost estimates of analogous systems. In addition, although any CIPT analyst could perform the task, the NCCA analyst should be responsible for developing the risk and uncertainty analysis since NCCA analysts are generally more experienced in such analyses. However, if the program manager's analyst performs the analysis, the NCCA analyst will be responsible for technical guidance and assistance.

In most cases, the program manager's analyst will be responsible for collecting the programmatic and technical data required as input values to the various cost estimating methodologies. This data, and particularly the associated risk data defined above, must be collected at the most appropriate level, depending on the analysis being done, prior to developing a cost estimate.

Historically, technical and programmatic data have been largely treated as constants. For example, an aircraft may be specified to weigh 22,000 pounds empty and to carry exactly 5000 rounds of ammunition. These numbers seldom come out exactly as specified. The responsibility of the program manager's analyst is to obtain reasonable bounds for these values, which may be used for risk analysis at a later time.

Therefore, whenever a value (e.g., quantity, weight, length) is obtained for future use in a cost estimate, it must be accompanied with a reasonable range based on consultation with knowledgeable individuals. Examples include "the aircraft's empty weight will most likely come in at 22,000 pounds, but may be as low as 21,000 pounds or as high as 25,500 pounds;" or "the gun's magazine is expected to carry between 4800 and 5200 rounds of ammunition when fully loaded."

Of course, there will be some values that contain no variability. These should be indicated also. An example might be "the torpedo must be exactly 24 inches in diameter since it has to fit into an existing unmodified launcher."

Finally, in order to do a meaningful risk and uncertainty analysis, all cost estimates that are derived from lower level data must be documented. For example, if the program office estimates a cost based on empty weight and magazine capacity, the risk and uncertainty analyst must have visibility into the values (and their associated ranges) that were used to develop the estimate. In addition, the cost analyst must document all CERs and cost factors to include statistical information such as variance, standard deviation, and coefficients of variation.

Procedures

The basic process required to perform a cost risk and uncertainty analysis is first to quantify each element of the cost estimate in terms of its statistical properties such as mean or average, standard deviation, range, most likely cost, lowest possible cost, or highest possible cost. Second is to perform a Monte Carlo simulation. With this technique one takes a random sample from the probability distribution of each cost element. The sum of all randomly sampled cost elements is then taken to be one random sample of the total cost. This procedure is repeated many times. The result of this process is a probability distribution about the cost estimate. Figure 1 displays a representative risk and uncertainty analysis of average unit production phase costs from a precision-guided munition program. This analysis is the result of 10,000 iterations using a commercial Monte Carlo simulation model. The mean cost is estimated at $33.1K, the standard deviation is $5.7K, and the range of nearly all possible outcomes is from $15K to $50K.

The mean, plus or minus one standard deviation, may be interpreted as the range in which one can be 68 percent sure the

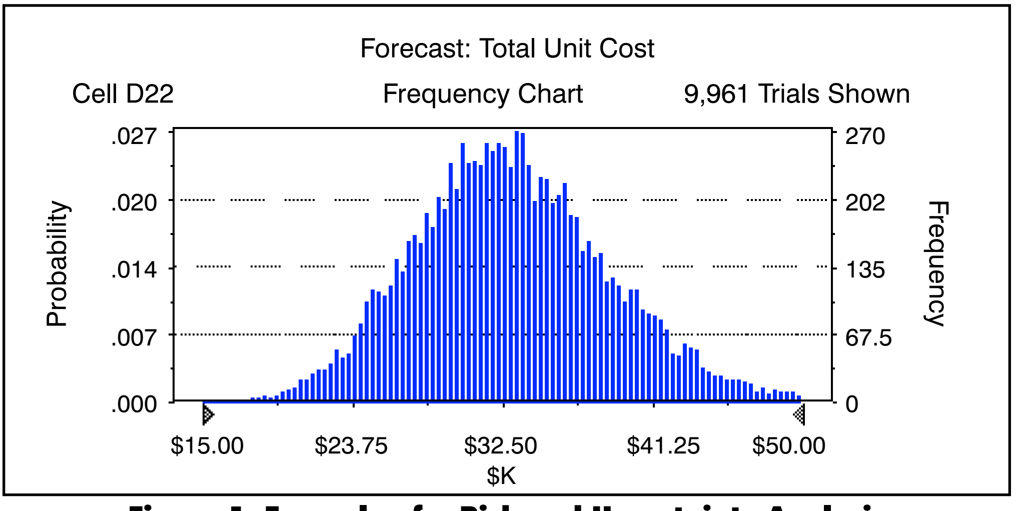

Figure 1. Example of a Risk and Uncertainty Analysis

true cost of the program will occur. Thus, in this example, the program manager can be 68 percent confident that the true average unit production phase cost for the baseline program will fall between $27.4K and $38.8K. Consequently, there is a 16 percent chance that the true cost will be below $27.4K and a corresponding 16 percent chance that the true cost will be higher than $38.8K. This information is much more useful to the program manager than the simple statement "the average unit production phase cost is estimated at $33.1K."

An Example Risk and Uncertainty Analysis

The following example of a risk and uncertainty analysis is intended to solidify the concepts discussed previously. In this example, a risk and uncertainty analysis will be performed on each individual work breakdown structure element using a Monte Carlo simulation. Additionally, an overall risk and uncertainty analysis will be conducted on the rolled up estimate using the same methodology.

Suppose you are asked to perform a risk and uncertainty analysis on a missile guidance and control (G&C) unit cost estimate (for expediency, learning curve phenomena will be temporarily ignored). The work breakdown structure for the G&C consists of a seeker and a processor.

Seeker Risk and Uncertainty Analysis

The program manager's cost analyst discussed the properties of the seeker with the engineer responsible for its design. The cost analyst has found a CER to estimate the unit cost of the seeker, which has operating frequency as its input variable. The CER is shown below.

$$\text{Seeker cost (FY 96 \$K)} = 0.41 \times (\text{Freq. in khz})^{0.78}$$
$$\text{Standard error} = 0.17\ (+18.5\%, -15.6\%)$$

According to the engineer, there is an 80 percent chance that the seeker will operate at 120 khz, but, due to design constraints, there is a corresponding 20 percent chance that it will operate at 80 khz. The risk associated with the seeker cost is a function of the choice of operating frequency (120 khz or 80 khz). The uncertainty is tied to the CER (+18.5%, –15.6%). This situation can be modeled as seen in Figure 2, where risk is modeled using a discrete probability distribution and uncertainty is modeled using a log normal probability distribution.

Based on a Monte Carlo simulation with 10,000 iterations, the mean unit cost estimate is $16.27K with a standard deviation of $3.37K1.[1] Therefore, we see a 68 percent chance that the true cost of the seeker will fall within the mean plus or minus one standard deviation ($12.90K to $19.64K) while the range of nearly all possible costs varies from approximately $7.50K to $27.50K.

[1] The mean and standard deviation reported here are actually the sample mean and sample standard deviation of the 10,000 data points resulting from the simulation. They are calculated as if the data were drawn from a normal probability distribution. As long as the resulting data set has a normal appearance (i.e., a bell-shaped curve), then the reported mean and standard deviation provide reasonable approximations of the true mean and standard deviation.

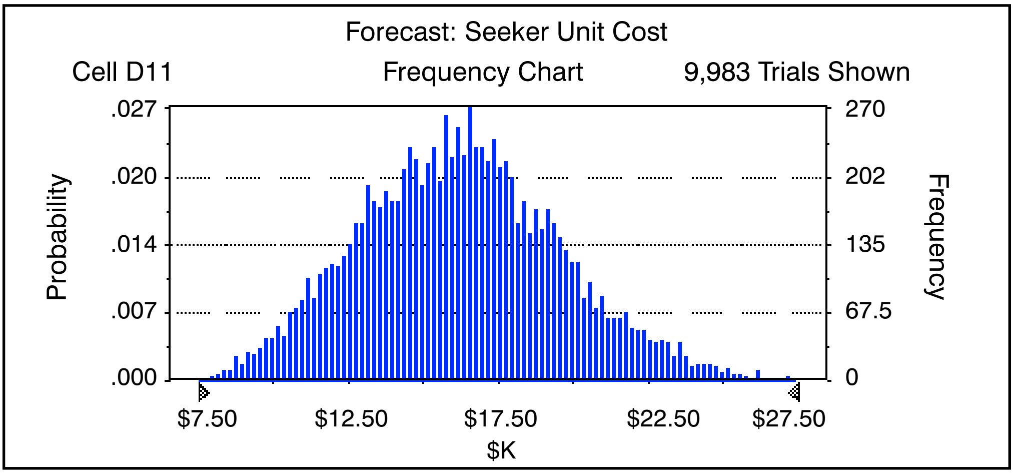

Figure 2. Seeker Risk and Uncertainty Analysis

In the absence of a risk and uncertainty analysis, the cost analyst might choose to estimate this cost element by calculating the seeker cost CER using a weighted average frequency.

> (120 khz) x (0.8) + (80 khz) x (0.2) = 112 khz
> Seeker cost = 0.41 x (112 khz)$^{0.78}$ = \$16.26K

Notice that the point estimate is nearly identical to the mean cost calculated using the Monte Carlo simulation. However, the risk and uncertainty analysis provides significantly more information to the program manager.

Processor Risk and Uncertainty Analysis

The program manager's cost analyst also discussed the properties of the processor with the engineer responsible for its design. According to the engineer, the processor is highly specialized and there are no analogous systems to be found. However, the analyst has found a CER that relates the unit cost of a processor to the number of zener diodes contained in the processor. The engineer has estimated the possible number of zener diodes inside the processor with a triangular distribution. According to the engineer, the minimum number of zener diodes is 10, the absolute maximum number is 30, and the most likely number is 15. The processor unit cost CER is as follows.

> Processor unit cost (FY 96 \$K) = 5.3 + 0.63 x (Number of zener diodes)
> Coefficient of variation = 22%

The risk associated with the processor is a function of the number of zener diodes required. The uncertainty is manifested in the coefficient of variation in the processor unit cost CER. This situation is modeled using a triangular distribution for the number of zener diodes and a normal distribution for the cost CER, as shown in Figure 3.

Based on a Monte Carlo simulation with 10,000 iterations, the mean unit cost estimate is \$16.83K with a standard de-

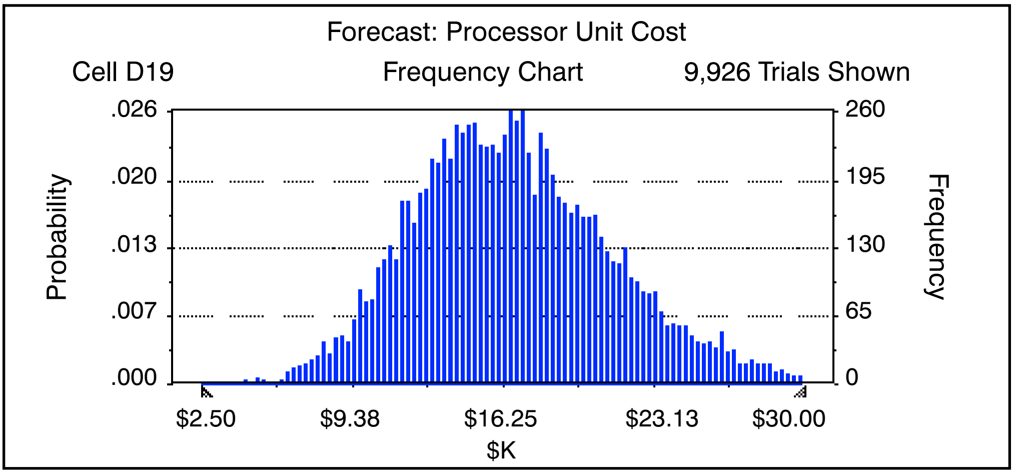

Figure 3. Processor Risk and Uncertainty Analysis

viation of $4.64K. Therefore, we see a 68 percent chance that the true cost of the processor will fall within the mean plus or minus one standard deviation ($12.19K to $21.47K), while the range of nearly all possible costs is approximately $2.50K to $30.00K.

Again, in the absence of a risk and uncertainty analysis, the cost analyst might choose to estimate this cost element by calculating the processor CER using the most likely number of zener diodes, which was stated earlier as 15.

Processor cost = 5.3 + 0.63 x (15) = $14.75K

Notice that in this case, the point estimate is quite a bit less than the mean cost calculated using the Monte Carlo simulation. This difference is primarily due to the risk associated with the wide range in the possible number of zener diodes.

TOTAL GUIDANCE & CONTROL RISK AND UNCERTAINTY ANALYSIS

The total unit cost for the guidance and control is the sum of the cost estimates for both the seeker and the processor. However, since we are no longer dealing in just point estimates, it is appropriate to run one more Monte Carlo simulation, where, on each iteration, the random observations for the seeker and processor are summed and the result is the random observation for the total unit cost. Figure 4 shows the results of this exercise.

Based on a Monte Carlo simulation with 10,000 iterations, the mean total unit cost is $33.10K. Note that this number is simply the sum of the mean costs for the seeker ($16.27K) and the processor ($16.83K), as one would expect. The standard deviation for this cost distribution, however, is $5.71K, which is less than the sum of the standard deviations for the seeker and processor. These phenomena are consistent with statistical theory.

The smaller standard deviation leads to an interesting result. When summed to-

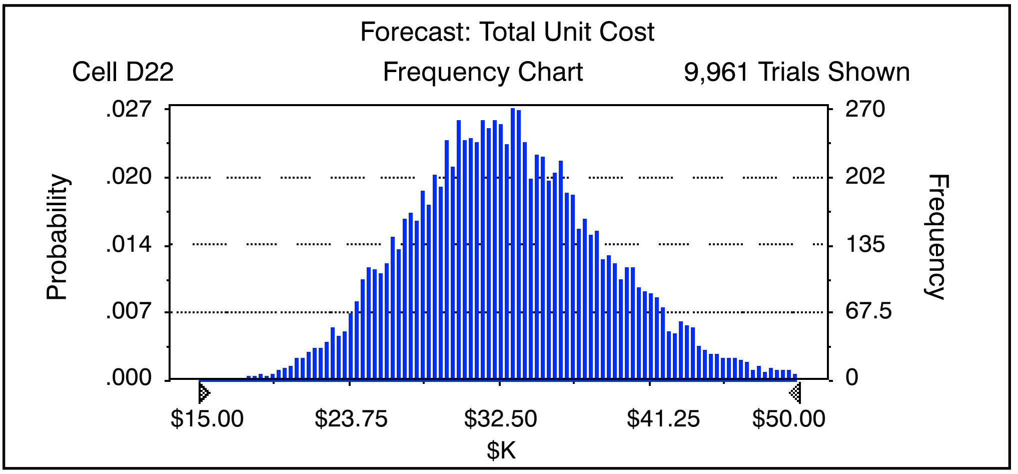

Figure 4. Total G&C Risk and Uncertainty Analysis

gether, the total unit cost estimate has a tighter range than if one had simply summed the endpoints of the two sub-elements. For example, the lowest observed cost for the seeker was $7.50K, while the lowest observed cost for the processor was $2.50K. Summed together, one might expect the lowest observed total cost to be $10.00K. However, since summing the two sub-elements has reduced the overall variance, we find in the simulation that the lowest observed total unit cost is actually $15.00K. A similar result occurs with the highest observed costs. Instead of the summed value of $57.50K, the simulation shows that the highest observed cost of the sum is actually only $50.00K. Thus, the more we aggregate the cost elements, the more precise our cost estimates using this methodology.

Therefore, for the total G&C, we have a 68 percent chance that the true cost will fall within the mean plus or minus one standard deviation ($27.39K to $38.81K) while the range of nearly all possible costs varies from $15.00K to $50.00K.

SUMMARY

This primer illustrates the benefits available to program managers and milestone decision authorities when a proper risk and uncertainty analysis is performed on a baseline cost estimate. What the reader should gain from this article is an appreciation of the superiority, from a decision-maker's perspective, of a point estimate with a risk and uncertainty analysis, as opposed to a point estimate alone. The reader should also understand the increased responsibility of the cost estimating analyst with respect to data collection, in that all data used in creating a cost estimate must include range or variability assessments.